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EXPERIMENTALLY DETERMINED RELATIONSHIP BETWEEN  
EXTINCTION AND LIQUID WATER CONTENT

APRIL 1981

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Simultaneous environmental chamber measurements have been made of $10.27\mu\text{m}$ extinction coefficients and liquid water content of droplet distributions with sizes spanning those of light to heavy fogs. The measurements yield a linear relation which is nearly independent of droplet size distribution, in agreement with recent calculated results and predictions. Liquid water content varied from 0.01 to 3.3 gm/m <sup>3</sup> , and droplet size distributions with single mode			

20. ABSTRACT (cont)

and bimodal differential extinction coefficient curves (extinction coefficient as a function of droplet size) were included. The spectral variation of extinction coefficient between  $9.2\mu\text{m}$  and  $10.8\mu\text{m}$  was also measured. The results are in good agreement with the variation calculated for typical droplet size distributions.

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## INTRODUCTION

An understanding of the effects of atmospheric constituents on the effectiveness of Army electro-optical systems, both actual and proposed, requires a basic understanding of relationships between propagation and meteorological or other source parameters.

This report describes simultaneous but independent measurements of the extinction coefficient due to various size distributions of water aerosols and the mass density of the water aerosol distributions. The liquid water content (LWC) measurements were made with two recently developed systems which are described in detail in Bruce et al.<sup>1</sup> The results are in general agreement with calculated results of Pinnick et al<sup>2</sup> based on measured fog droplet size distributions and give further verification to Chylek's<sup>3</sup> prediction of a unique linear relation between extinction at approximately 11 $\mu$ m and LWC of fogs for all size distributions with maximum particle radii less than or approximately equal to 14 $\mu$ m.

## EXPERIMENTAL APPROACH

The measurements were made in an environmental chamber having a volume of approximately 1 cubic meter. Water droplets were generated within the chamber, and minimum stirring was used to ensure uniform spatial distribution of the particles.

Figure 1 is a diagram of the optical system used in the extinction coefficient measurements. The (half power) diameter of the laser beam is approximately 1 cm in the measurement region. Early measurements made with a larger diameter (x 3) beam did not significantly improve the steadiness of the transmitted signal. The laser path through the chamber is in the vertical direction with a total length of 1.79 m. Warm dry air in the form of a thin sheet is blown across the (exterior) mirrors at the top and bottom of the chamber to prevent accumulation of water droplets on the mirror surfaces. A sample of the input beam is monitored by a reference power meter. Calculations and parametric measurements have been used to determine the attenuation necessary to prevent significant heating and evaporation of the water droplets. A mirror is rotated into the beam path to direct the beam to a spectrum analyzer during tuning of the laser.

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<sup>1</sup>C. W. Bruce, R. J. Brewer, and H. Burkett, A System for Measurement of Liquid Water Content, to be published as an ERADCOM report

<sup>2</sup>R. G. Pinnick, S. G. Jennings, P. Chylek, and J. H. Auermann, 1979, "Verification of a Linear Relation Between IR Extinction, Absorption and Liquid Water Content of Fogs," J Atmos Sci, 37:1577-1586

<sup>3</sup>P. Chylek, 1978, "Extinction and Liquid Water Content of Fogs," J Atmos Sci, 35:296-300

Sampling throats for the LWC measuring systems are located approximately in the lower center of the chamber. Sampling is at a rate of 10 to 15 liters per minute. The sampling throat of a commercial light scattering counter extends through one side of the chamber to a point close to the extinction path and the LWC sampling throats. This instrument is used to monitor the droplet size distributions and, through these, the contributions of different size particles to the extinction coefficient (differential extinction coefficient).

#### PRELIMINARY EXPERIMENTS

Although the measurement systems used in this study are relatively simple, several extensive preliminary investigations were conducted to provide the existence of appropriate experimental operating conditions.

The first of these investigations involved the commercial instrument used to monitor the particle size distributions--a Particle Measuring Systems (PMS) classical scattering aerosol spectrometer. This instrument is sensitive to water droplets with radii from 0.1 $\mu$ m to 16 $\mu$ m.

This instrument counts particles of different sizes by pulse height analysis of laser light (0.65 $\mu$ m) scattered by single particles into a particular solid angle. Determination of particle size is indirect because the scattering depends on particle refractive index and on the geometry of the optical system.

The instrument used in this study was checked to be sure that particles were counted in the correct size range channels. Single-size nearly transparent beads were used for channels counting particles with radii up to about 4 $\mu$ m and calibrated bead mixtures were used for channels counting particles with radii between 4 $\mu$ m and 16 $\mu$ m. Particle counting efficiency was not measured. The results from the studies with mixed bead sizes indicate that counting efficiency was relatively constant for all channels since the curves obtained with calibrated bead mixtures had the correct shapes for the size mixtures used.

Care must be exercised to limit the density of aerosol sampled by the counter since counting is based on the assumption of single scattering by individual particles and distortion of results may occur at high count rates. A variety of dilution techniques was tried in which droplet-free air was mixed with the droplet sampling stream from the chamber in the inlet throat of the PMS counter. Care was taken to minimize disturbance of the flow character. The results obtained indicate that use of these techniques extended the number density range of the instrument by a factor of about 3, but that further dilution caused definite distortion of the differential extinction curves. The differential extinction curves were used only in a relative sense; that is, the shape of the curve and the particle radius,  $r_p$ , at which peak extinction occurred were used as characteristic parameters of the chamber droplet distributions since an absolute calibration was not available to relate a measured size distribution to actual extinction coefficients and LWC.

The second of these preliminary studies was an investigation of the conditions for generation of droplet size distributions and differential extinction profiles within the ranges found in naturally occurring light to heavy fogs. Differential extinction profiles show the contribution to extinction of particles with radii in relatively small size ranges. Peak extinction for fogs normally occurs in the particle radius range of  $2\mu\text{m}$  to  $10\mu\text{m}$ . No attempt was made to specifically tailor size distributions to be representative of any particular type of fog but rather to span typical fog droplet sizes. Maximum droplet size was approximately  $16\mu\text{m}$  to permit accurate monitoring of the size distributions by the PMS spectrometer.

Commercially available "cool mist vaporizers" were used to generate droplet distributions which had monomodal differential extinction curves. The radius of peak extinction,  $r_p$ , could be varied from about  $8\mu\text{m}$  to  $16\mu\text{m}$  by using a variety of throttling and impaction techniques. A stable mode of operation with peak extinction at particle radii of  $10\mu\text{m} \pm 1\mu\text{m}$  was finally used. Condensation droplet distributions were produced by introducing cold gaseous nitrogen into the saturated vapor of the chamber. These distributions are characterized by relatively narrow, monomodal differential extinction curves with peak extinction for droplet radii of  $4\mu\text{m} \pm 1\mu\text{m}$ . Both types of droplet distributions were generated with densities ranging from about 0.01 to  $4.0\text{ gm/m}^3$ . The shape and peak position of the differential extinction curves were not particularly sensitive to variation of the droplet number density. Typical differential extinction curves are shown in figure 2.

A study of the spatial uniformity of the droplet distributions was made by varying the location of the droplet generators and using several stirring mechanisms. Most of the mixing results from the circulation caused by the droplet generators. A small fan with specially tailored blades provides the small additional circulation (in the form of a donut within the chamber) required to obtain spatially uniform distributions.

The last of the preliminary studies involved characterization of two new sensing systems which give real-time measurements of LWC. These instruments and their characterization will be reported in detail elsewhere.<sup>1</sup> Only a summary will be given here.

One system involves a mass accumulation technique in which droplets are collected on a three-dimensional filter consisting of layers of flannel on a screen base. If the accumulated mass is measured and divided by the sampling time and the volume flow rate through the filter, an absolute measurement of LWC is obtained in units of mass density. The three-dimensional filter is critical to successful measurements since water droplets would clog a two-dimensional filter and lead to inaccurate sampling. Sampling times between 15 s and 4 min were used for light and heavy mass density droplet distributions and have yielded reproducible results.

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<sup>1</sup>C. W. Bruce, R. J. Brewer, and H. Burkett, A System for Measurement of Liquid Water Content, to be published as an ERADCOM report

Caution is necessary in this measurement to apply a time-dependent correction factor which results from quite rapid initial absorption of water by the dry filter fibers. This effect actually represents equilibration of the flannel to the relative humidity of the chamber. Since this effect is rapid and reproducible, the necessary correction is straightforward. Mass collection was studied to determine an adequate number of layers of flannel.

For the environmental chamber measurements, filters are preweighed in sealed containers, inserted into a sampling throat with O-ring seals, and replaced in their original container for post sampling weighing. They are then dried with a stream of ambient air for later use. A similar but real-time system is incorporated into a top loading electronic balance is also used.

The second LWC measurement system uses a differential sampling technique with phase-sensitive detection. The system has two sampling throats. One throat is vertical and unobstructed, and the flow through it contains both vapor and water droplets; the other throat contains a series of flannel filters with offset openings which create free-flow conditions through a tortuous path so that the resulting sample contains only vapor. A rotating half disc alternately selects samples from the two throats and permits them to flow through a heated woven wire grid which evaporates the droplets. The wire diameter was chosen to be much larger than the water droplets to provide a good evaporation efficiency. Evaporation of water from the grid causes cooling and a change in the grid resistance. This change results in an approximately linear change in the voltage applied across the grid by a constant current power source. The reference signal for a lock-in amplifier is obtained from the throat selected by half disc, and the synchronous voltage change across the grid is measured. The resulting signal has been shown to be proportional to the total mass density measured with the filter system in a series of measurements over a wide range of environmental chamber conditions. Single and multiple layer grids have been used, and no significant difference in results was found.

The mass collection (filter) system is used to establish the calibration of the differential system. For these measurements, the system has been used as a continuing check on the calibration; but the stability of the differential system is sufficient that such monitoring is not actually necessary.

#### EXPERIMENTAL PROCEDURES

Most of the extinction coefficient measurements in this study were made with the laser tuned to the 10 $\mu$ m R-16 CO<sub>2</sub> transition line at a wavelength of 10.27 $\mu$ m. However, several sets of spectral scans of both the 9 $\mu$ m and 10 $\mu$ m R and P bands of CO<sub>2</sub> were made. The laser beam power was monitored continuously, prior to the input mirror for the fog chamber (sampled by a beam splitter) and after it left the chamber. The length of the path within the chamber was 1.79 m.

Optical alignment and laser line stability were periodically checked and no problems were encountered. The power meters and the differential LWC system were stabilized, and baselines were established on the chart recorders used for data collection.

The droplet generators were then turned on, and the chamber was brought to a droplet equilibrium condition which was characterized by constant values for both transmitted laser power and differential LWC signals. After recording these values, the droplet generators were turned off, and the chamber was again allowed to reach an equilibrium with only vapor present. This procedure establishes a baseline for the measurement of changes in transmission of laser power due to droplets only.

The droplet generators were again turned on; and after equilibrium conditions were reached, a set of three filter measurements of LWC was made. PMS counter measurements were then made, and the droplet generators were turned off. After a settling time to return to vapor-only conditions, the same measurement process was repeated with a different power supplied (by use of a Variac) to the droplet generators. Variac settings between 60 and 100 percent were used to provide a variety of droplet number densities. Size distributions and the shape and position ( $r_p = 10\mu\text{m} \pm 1\mu\text{m}$ ) of the differential extinction coefficient curves remained almost constant for all similar sets of experiments.

Different droplet size distributions were obtained by following the above procedure for establishing vapor saturation as well as equilibrium droplet conditions and then introducing cold nitrogen gas into the center of the chamber. After an initial mixing period of about 1 min, chamber conditions became essentially uniform; then both the transmitted laser power and differential LWC signals decayed (over a period of 6 to 10 min) back to those representative of ambient temperature conditions.

For some of these condensation droplet measurements, the droplet generators were turned off before the cold nitrogen was introduced. Under these conditions, the position of  $r_p$  for the differential extinction coefficient curves was at about  $4\mu\text{m} \pm 1\mu\text{m}$ .

When the droplet generators continued operation, the position of  $r_p$  either occurred at an intermediate position or the size distribution was bimodal with a variety of shapes and the two peak extinction positions within the range of  $4\mu\text{m}$  to  $10\mu\text{m}$ .

Since chamber conditions varied with time for these condensation experiments, the LWC filter measurements were made only under the original equilibrium conditions to establish a calibration value for the differential LWC measurement.

The PMS counter measurements also required a special procedure. Since the counter significantly depleted the chamber's contents, size distributions were measured on alternate measurement sets for repeated conditions. There was an equilibration period when the counter was first turned on. The data for this period (about 3 s) were discarded. Then, several valid 2 s sampling sets of data were obtained.

The spectral variation of extinction was also measured. Two types of experiments were performed. In the first the specially modified laser was operated in a scanning mode. In this mode the laser can be scanned through the  $9\mu\text{m}$  R and P bands and then, with a minor adjustment, through the  $10\mu\text{m}$  R and P

bands. A complete scan of these bands takes approximately 1 h. These data were somewhat noisy so another experimental procedure was also used.

The second set of spectral data was obtained by manually tuning the laser to four separate spectral lines in each of the four bands and measuring the extinction. The lines used (10, 18, 24, and 30) were chosen to be fairly evenly distributed across each band. Data were taken by using the same general procedures as those used in the other experiments, with droplet generation conditions typical of those which produced differential extinction peaks at approximately 10 $\mu$ m.

Environmental chamber conditions for these spectral scans were the same as the conditions for equilibrium droplet generation for the detailed 10, 18, 24, and 30 experiments. No condensation droplet distributions were included since these were unstable, and the experiments would be time-consuming and difficult to interpret.

## RESULTS

The measured relationship between the extinction coefficient at 10 $\mu$ m and the LWC of environmental chamber droplet distributions is shown in figures 3a through 3c.

Each type of size distribution clearly shows a linear relation between the measured quantities. The ratio between them shows some variation as a function of the droplet distribution generation mechanism: the slope for mechanically generated distributions (figure 3a) is 152  $\text{km}^{-1}/(\text{gm}/\text{m}^3)$ , for condensation droplet distributions (figure 3b) 158  $\text{km}^{-1}/(\text{gm}/\text{m}^3)$ , and for the combination of distributions (figure 3c) 156  $\text{km}^{-1}/(\text{gm}/\text{m}^3)$ , although it could presumably vary anywhere between the other two values.

However, the data for all of the distributions may be combined to yield a linear relation with a slope of 154  $\text{km}^{-1}/(\text{gm}/\text{m}^3)$  with a combined experimental error of 12  $\text{km}^{-1}/(\text{gm}/\text{m}^3)$  or 8 percent.

The PMS counter measurements of the size distributions were used in a Mie scattering program calculation of LWC and extinction coefficient (using a previously measured value for the complex index of refraction for water at this wavelength by Hale et al.<sup>1</sup>). The ratio of the calculated quantities of  $156 \pm 17 \text{ km}^{-1}/(\text{gm}/\text{m}^3)$  agrees within the experimental error with that of the measured slopes. This agreement was true even though the calculated values of the extinction coefficients and LWC were close to the measured values for one counter used but were very different for another similar unit.

Figure 4 is a comparison of the average measured extinction for each spectral band with the values calculated from measured droplet size distributions.

<sup>1</sup>G. M. Hale and M. R. Querry, 1973, "Optical Constants of Water in the 200-nm to 20 $\mu$ m Wavelength Region," Appl Opt, 12:555-563

Averages of both sets of measurements are shown, with the RMS data spread shown for the data set obtained by manually tuning the laser. The data taken with automatic tuning have a larger spread. Some of the lines measured in this mode of operation were not included in the band averages. These averages were chosen by plotting measured power for all lines in a band and discarding points which did not fall close to a Boltzmann-like profile. Approximately six lines (38 percent of total) were included in each average. The measured averages are plotted at the median wavelength for the lines used.

Two sets of calculated extinction coefficients are shown. These sets give the calculated spectral dependence of the extinction coefficient for typical droplet distributions with primarily large and small droplet sizes. The peak differential extinction coefficients occurred at approximately 8.8 $\mu\text{m}$  and 4.2 $\mu\text{m}$  for the droplet distributions used.

All data have been scaled to agree at 10.3 $\mu\text{m}$  since the other measurements reported here show that the extinction coefficient is independent of droplet size distribution and linearly dependent on LWC at that wavelength.

#### CONCLUSIONS

Measurements have been made of the extinction coefficient at 10.27 $\mu\text{m}$  and, independently, of the LWC of a large number of environmental chamber droplet size distributions with radii spanning those of a variety of fogs. A linear relation has been found which is approximately independent of the size distribution. The measured ratio of extinction coefficient to LWC is 159  $\text{km}^{-1}/(\text{gm}/\text{m}^3)$ .

These results are in good agreement with the linear relation predicted by Chylek<sup>1</sup> and calculated by Pinnick et al<sup>2</sup> at 11 $\mu\text{m}$  based on size distribution measurements of fogs and hazes.

Measurements of the spectral dependence of the extinction coefficient (between 9.2 $\mu\text{m}$  and 10.8 $\mu\text{m}$ ) have been made and are in good agreement with the dependence calculated for two typical droplet size distributions.

Systems for the measurement of LWC under field conditions have been developed from those used in this study and were used in the Meppen 80 field tests.

The results obtained from the experiments reported here suggest that it would be possible to use measurements of LWC to predict performance in fogs and hazes of EO systems operating in the 10 $\mu\text{m}$  atmospheric window.

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<sup>1</sup>P. Chylek, 1978, "Extinction and Liquid Water Content of Fogs," J Atmos Sci., 35:296-300

<sup>2</sup>R. G. Pinnick, S. G. Jennings, P. Chylek, and J. H. Auermann, 1979, "Verification of a Linear Relation Between IR Extinction, Absorption and Liquid Water Content of Fogs," J Atmos Sci., 37:1577-1586

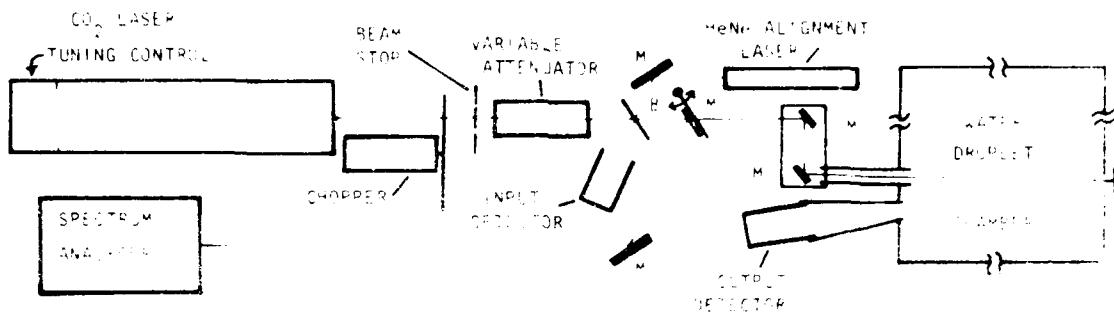


Figure 1. Optical system. M represents mirrors. B represents beam splitter. One mirror is rotatable to permit laser line identification. The CO<sub>2</sub> laser incorporates automatic line scanning and stabilization. An optical beam chopper is retained so that an aerosol spectrophotometer measures absorption coefficient and alternate detectors for other lasers may be used. An adjustable aperture for the CO<sub>2</sub> laser beam, window flush for the input and output mirrors, liquid water content measurement systems, and particle counter are omitted in this diagram.

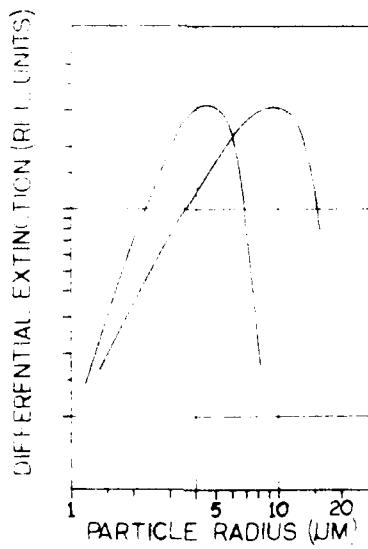
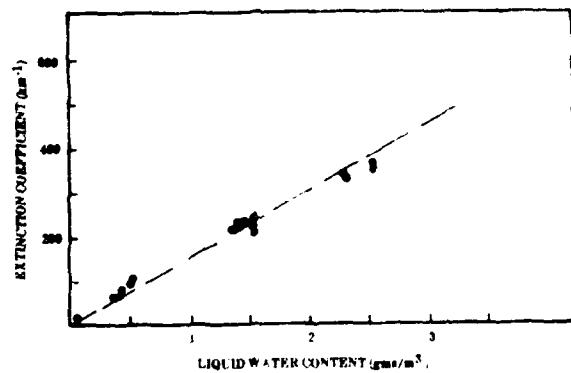
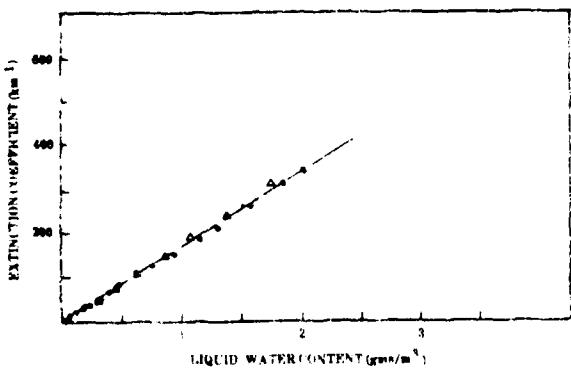


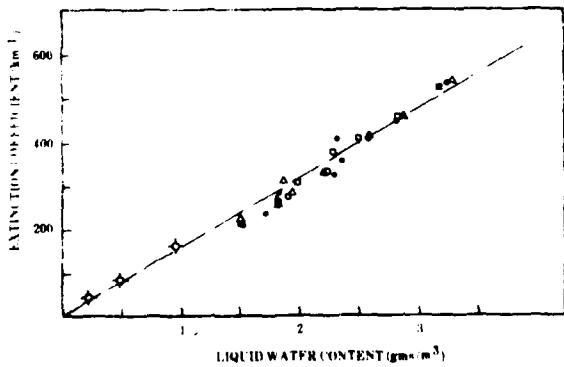
Figure 2. Typical differential extinction curves for condensation droplet (left peak) and mechanically generated (right peak) size distributions.



(a) Mechanically generated droplet size distributions.



(b) Condensation droplet size distributions.



(c) Droplet distributions generated by combinations of the mechanical and condensation techniques.

Figure 3. Extinction coefficients as functions of liquid water content for mechanically generated, condensation, and combination droplet size distributions.

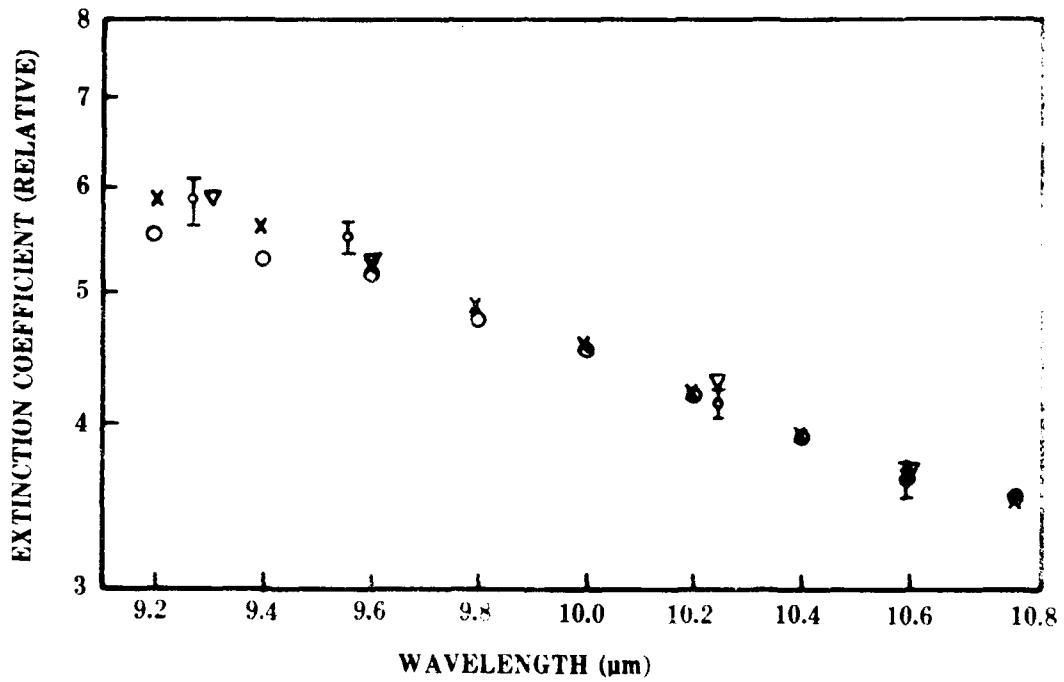


Figure 4. Measured and calculated extinction coefficients. The measured data points are averages for the spectral band plotted at the median wavelength for the lines used. The RMS data spread is indicated for the manually tuned measurement set ( $\Phi$ ). The data spread for the automatically scanned measurements ( $\nabla$ ) is of the same order of magnitude. The calculations are for typical droplet size distributions with peak differential extinction at droplet radii  $r_p$  of approximately  $8.8\mu\text{m}$  ( $\circ$ ) and  $4.5\mu\text{m}$  ( $\times$ ).

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